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Citation for published version:

Cutter, MG, Martin, AE & Sturt, P 2019, 'Capitalization interacts with syntactic complexity', *Journal of Experimental Psychology: Learning, Memory, and Cognition*, vol. 46, no. 6, pp. 1146-1164.
<https://doi.org/10.1037/xlm0000780>

Digital Object Identifier (DOI):

[10.1037/xlm0000780](https://doi.org/10.1037/xlm0000780)

Link:

[Link to publication record in Edinburgh Research Explorer](#)

Document Version:

Peer reviewed version

Published In:

Journal of Experimental Psychology: Learning, Memory, and Cognition

Publisher Rights Statement:

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Capitalization Interacts with Syntactic Complexity

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Word Count: 16293

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This research was supported by the Leverhulme Trust Research Project Grant RPG-2017-049.

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Data files and R Scripts used in the analysis of our paper are available at <https://osf.io/ep7yd/>. The data from Experiment 1 were presented at the CUNY Conference on Human Sentence Processing in Davis, California (March 2018) and a meeting of the Experimental Psychology Society in Leicester, UK (April 2018).

Abstract

We investigated whether readers use the low-level cue of proper noun capitalization in the parafovea to infer syntactic category, and whether this results in an early update of the representation of a sentence's syntactic structure. Participants read sentences containing either a subject relative or object relative clause, in which the relative clause's overt argument was a proper noun (e.g., *The tall lanky guard who alerted Charlie/Charlie alerted to the danger was young*) across three experiments. In Experiment 1 these sentences were presented in normal sentence casing or entirely in upper case. In Experiment 2 participants received either valid or invalid parafoveal previews of the relative clause. In Experiment 3 participants viewed relative clauses in only normal conditions. We hypothesized that we would observe relative clause effects (i.e., inflated fixation times for object relative clauses) while readers were still fixated on the word *who*, if readers use capitalization to infer a parafoveal word's syntactic class. This would constitute a syntactic parafoveal-on-foveal effect. Furthermore, we hypothesised that this effect should be influenced by sentence casing in Experiment 1 (with no cue for syntactic category being available in upper case sentences) but not by parafoveal preview validity of the target words. We observed syntactic parafoveal-on-foveal effects in Experiment 1 and 3, and a Bayesian analysis of the combined data from all three experiments. These effects seemed to be influenced more by noun capitalization than lexical processing. We discuss our findings in relation to models of eye movement control and sentence processing theories.

Keywords; eye movements; parafoveal-on-foveal effects; relative clause processing; parafoveal processing.

During reading, several complex processes are tightly coordinated. These include lexical processing, the programming of saccadic eye movements, the parafoveal processing of yet-to-be fixated words, and the integration of each new piece of linguistic input into a syntactic structure (see Rayner, 2009, for a review). Yet little is known about how information from low-level visual analysis accrues into the complex linguistic meanings we perceive during reading. Furthermore, there has been relatively little consideration of how syntactic parsing may be influenced by information available in the parafovea, and how the syntactic class of a word still in the parafovea may influence eye movement behaviour. It is these issues which we investigate in the current paper, by testing whether readers can detect a capitalised proper noun in the parafovea during reading, and whether this results in measurable processing difficulty while this word remains in the parafovea.

Parafoveal processing

Parafoveal processing refers to the processing of information from words that have yet to be directly fixated. Controversy exists about what kind of information is extracted from parafoveal words and the time-course across which this information is extracted, with this issue being highly relevant to the debate between computational models of eye movement control (outlined below) which assume that lexical processing occurs in either a serial or parallel manner. Parafoveal processing has typically been examined in relation to three phenomena, with these being parafoveal-on-foveal effects, word skipping, and preview benefits. The current paper focuses on the first of these, but it is important to outline the basics of all three. Parafoveal-on-foveal effects relate to the idea that fixations on a word (referred to henceforth as word n) may be influenced by the characteristics of the following word (referred to henceforth as word $n+1$), and are taken as evidence that these two words may be processed at the same time. Word skipping refers to how often a word is skipped, and is taken as evidence that a word has been processed to a great enough extent in the parafovea

that it does not require direct fixation. As such, any variables that influence word skipping rates (e.g., length, frequency) are considered to be processed parafoveally. Finally, preview benefit is assessed using the boundary paradigm (Rayner, 1975), in which an invisible boundary is placed in front of a target word, and prior to the eye crossing this boundary there is either a correct or incorrect preview of the target word, which changes to the target word as the boundary is crossed. Fixation times on this word are assessed as a function of whether participants received a correct or incorrect preview, with fixations being shorter in the former case. This effect is referred to as a preview benefit. Beyond this basic effect, previews which share certain characteristics with the target (e.g., phonology; see Cutter, Drieghe, & Liversedge, 2015 for a review and Vasilev & Angele, 2017 for a Bayesian meta-analysis) result in shorter target fixation times than previews which do not share these characteristics.

Recent results suggest that the extent to which readers process a parafoveal word is increased when this word is a capitalised noun. Specifically, Rayner and Schotter (2014) presented participants with correct, semantically related, or unrelated previews of English nouns which could be presented as uncapitalised common nouns (e.g., *apple*) or capitalised proper nouns (e.g., *Apple* as the brand). Identity preview effects on the target word were numerically larger for capitalised than uncapitalised nouns, and semantic preview benefits were only observed for capitalised nouns. This suggests that readers are able to process the salient capital letter at the start of a parafoveal noun, and that this leads to a deeper level of parafoveal processing. One explanation for this is that capitalization allowed participants to rapidly identify the upcoming word as a (proper) noun. Whatever the locus of this effect, readers are clearly able to detect noun capitalization information in the parafovea.

Recent work has also established that readers extract information about syntactic class from words in the parafovea. Brothers and Traxler (2016) demonstrated that readers process the syntactic class of a word in the parafovea to such an extent that they are less likely to skip

a word that is syntactically illegal in a sentence frame than a word that is syntactically licit. Snell, Meeter, and Grainger (2017) observed similar effects, in addition to a syntactic preview effect whereby participants would fixate a target word (e.g., *jumps*) for less time when its preview was of the same syntactic class (e.g., *waved*) as opposed to a different syntactic class (e.g., *table*). Veldre and Andrews (2018) found that readers are less likely to skip a word when it violates subject/verb agreement or verb tense rules, in addition to observing a preview benefit for a preview that was a syntactically valid continuation of a sentence relative to a word that was not. Together, these studies suggest that readers extract syntactic information from the parafovea, with effects on both word skipping and preview effects. However, none of these studies showed that these syntactic manipulations affected fixations prior to the syntactically illegal words (i.e., a parafoveal-on-foveal effect). In the current study we tested whether a syntactic parafoveal manipulation has an even earlier effect in cases when parafoveal syntactic class is cued by proper noun capitalization.

Parafoveal-on-foveal effects

As mentioned above, parafoveal-on-foveal effects refer to the idea that fixations on word n can be influenced by the characteristics of word $n+1$. While the idea that information is extracted from a word in the parafovea is uncontroversial, there is considerably more disagreement regarding whether this occurs early enough to affect viewing times on the fixated word, with serial models of eye movement control generally not predicting such effects while parallel models do predict these effects. In brief, this is due to the idea that in serial processing models the parafoveal word should not be processed prior to the fixated word being fully identified, while in parallel models both of these words are processed at the same time. Before outlining the specific mechanisms of these models that make these predictions, we will survey the current evidence for parafoveal-on-foveal effects.

There has been much dispute regarding whether readers experience lexical parafoveal-on-foveal effects, whereby lexical characteristics, such as the frequency of word $n+1$, affect fixations on word n . The current state of this debate can be summarized as offering little evidence for effects at a lexical level, with two recent studies being noteworthy. Angele et al. (2015) conducted a corpus analysis, in which reading times on every word in a set of sentences were assessed as a function of the characteristics of word n and word $n+1$. This analysis demonstrated that fixation times on word n were influenced by the frequency of word $n+1$, which in prior similar studies was taken as evidence for parafoveal-on-foveal effects. However, crucially, these effects were still observed when word $n+1$ was masked with a series of xs, preventing the processing of this word. This suggests that these effects are not actually due to readers processing word $n+1$, but rather to some unknown correlated variable. This study is important, since the evidence for these effects has come from eye-movement corpora, rather than controlled experiments. However, Angele et al.'s study suggests that such findings should be treated cautiously, especially without evidence for these effects from well-controlled experiments. It is to this lack of evidence that we turn next.

Brothers, Hoversten, and Traxler (2017) conducted four experiments with a high level of statistical power testing for a parafoveal-on-foveal effect of the frequency of a target word in a controlled experimental design. Furthermore, they performed a Bayesian meta-analysis of similar prior studies. In addition to not finding parafoveal-on-foveal effects in their own experiments, the Bayesian meta-analysis revealed strong evidence in favour of the null hypothesis (i.e., no parafoveal-on-foveal effects) in studies examining effects of parafoveal word frequency, plausibility, and predictability. Thus, this study suggests that across many controlled experiments, there is evidence against lexical parafoveal-on-foveal effects.

While current evidence is against lexical parafoveal-on-foveal effects, there is evidence for orthographic parafoveal-on-foveal effects. White (2008) found that readers

fixated word n for longer when word $n+1$ was orthographically unfamiliar (i.e., its individual letters, bigrams, and trigrams occur relatively infrequently, as in *crypt*) than when it was orthographically familiar (i.e., its individual letters, bigrams, and trigrams occur relatively frequently, as in *adder*), while Drieghe, Rayner, and Pollatsek (2008) showed that readers would fixate word n for longer when it was followed by an orthographically illegal non-word (e.g., *pvxforming* compared to *performing*). These effects suggest that readers are able to pick up on salient orthographic information prior to direct fixation, to an extent that it impacts pre-target fixation durations. However, it should be noted that these effects are primarily restricted to the last fixation on a pre-target word, and, in the case of Drieghe et al.'s study, to trials in which this fixation was made on the final character of the pre-target word. Thus, while such effects are generally acknowledged to be real, they are still fairly small.

To summarise, the existing literature suggests that while low-level orthographic information in the parafovea can influence fixation durations on an earlier word, lexical information cannot. Furthermore, recent studies (Brothers & Traxler, 2016; Veldre & Andrews, 2018) suggest that readers are sensitive to syntactic information in the parafovea to the extent that both word skipping and preview effects are influenced by the sentential fit of a parafoveal word, although these syntactic manipulations do not result in parafoveal-on-foveal effects. It is unsurprising that these syntactic effects do not appear on a pre-target word, given that in the vast majority of cases a word must be lexically processed to some extent for its syntactic class to be retrieved. However, in some cases the syntactic class of a word can be signalled via low-level visual cues, such as by the capital letter at the beginning of a proper noun. In these cases, effects of syntactic manipulations may occur earlier, due to being driven by low-level orthographic cues as opposed to lexical retrieval. This would be interesting for several reasons. First, it would suggest that readers do indeed make use of visual cues in order to infer a word's syntactic class. Second, it would demonstrate that a form of linguistic

processing does indeed play a role in parafoveal-on-foveal effects, as opposed to these effects simply being driven purely by unusual visual information drawing attention away from the fixated word. Finally, it would suggest that, when possible, readers attempt to instantly integrate incoming syntactic information into a sentential representation, even in cases when this word has yet to be fully lexically processed.

Before proceeding, it is worth considering whether prior research already suggests an effect of proper noun capitalisation on a preceding word. As mentioned above, Rayner and Schotter (2014) presented participants with sentences containing either a capitalised proper noun or uncapitalised common noun. They examined the influence of this manipulation on gaze durations on the word before the noun, finding no parafoveal-on-foveal effects. Furthermore, in a re-analysis of this experiment (presented below) we confirm the absence of an effect in both go-past time and last fixation duration for this study. However, Hohenstein and Kliegl (2013) have examined this possibility in a less controlled corpus analysis, using data from participants reading German sentences that were either presented in normal sentence casing or entirely in lower case. In German all nouns are presented with their first letter capitalised. Hohenstein and Kliegl (2013) found that participants fixated on a word followed by a capitalised noun for longer than one followed by an uncapitalised noun. However, due to the nature of Hohenstein and Kliegl's data set, it is difficult to determine the exact locus of this effect. Presumably, within Hohenstein and Kliegl's data set, nouns sometimes appeared in positions in which they would be considered syntactically difficult; these cases could well have been driving their effects on their own. Alternatively, it could be the case that all capitalised nouns result in a parafoveal-on-foveal effect regardless of difficulty, simply due to being visually salient. Within English, at least, this seems unlikely, given the null results observed by Rayner and Schotter (2014). In the current paper we

attempt to establish whether there is a parafoveal-on-foveal effect of capitalised words in English by using capitalised nouns to signal difficult syntactic structures to participants.

Models of eye movement control

As mentioned above, various computational models of eye movement control have been proposed, which make differing assumptions about the timecourse of lexical processing, as well as several other aspects of the reading process. Before proceeding, it is worthwhile outlining the two dominant models of oculomotor control during reading. An understanding of the time-course of lexical processing, parafoveal processing, and saccadic programming will be important in the interpretation of our data. In the E-Z Reader model (Reichle, Warren, & McConnell, 2009) it is assumed that eye movements are primarily driven by lexical processing, with this occurring on a serial, word-by-word basis. There are two stages of lexical processing (L_1 and L_2), with L_1 involving an assessment of a word's familiarity, and L_2 involving the word being lexically accessed. Once L_1 has been completed, readers begin programming a saccade to word $n+1$, in parallel with L_2 . The L_2 stage will often finish prior to a saccade program being ready, with processing beginning on word $n+1$ while the eyes remain on word n . Once a saccade program is ready, the eye moves onto word $n+1$. This temporary dissociation between attention and fixation location accounts for preview benefits that can be measured in fixation times on word $n+1$. The link between lexical processing and saccadic programming precludes E-Z Reader from predicting lexical parafoveal-on-foveal effects; since readers begin programming a saccade away from word n prior to word $n+1$ being processed, the properties of word $n+1$ cannot influence the timing of the saccade away from word n . However, it has been proposed that orthographic parafoveal-on-foveal effects can be explained by a pre-attentive visual stage of processing (Reichle, Pollatsek, & Rayner, 2006). E-Z Reader also makes assumptions about the integration of identified words into a sentential representation. The post-lexical integration stage for a word includes integrating

that word into a syntactic structure and begins immediately after L_2 completion. It is assumed that this stage of processing will only influence eye movement behaviour when there is a rapid integration failure (e.g., due to a word representing a syntactic violation within the sentence) or when integration is difficult enough that a reader cannot integrate this word prior to identifying the following word. In both cases, the eyes and attention will be directed back towards this word, which will be re-processed starting from L_1 . This can impact fixation behaviour in several ways, including refixations being made on word n if the eyes have not yet left it, or regressions being made to word n if the eyes have already left it, which can also result in longer fixations on word $n+1$ due to a regressive saccade taking longer to program than a progressive saccade.

The SWIFT model (Engbert, Nuthmann, Richter, & Kliegl, 2005) makes several different theoretical assumptions. In this model fixation durations are determined by a random timer, with a saccade being programmed once this reaches a random arbitrary value. While this timer's duration is random, it can be inhibited by the processing difficulty of word n , such that difficult words slow the timer down. It is not just the fixated word that is processed in SWIFT. Rather, several words in the parafovea may be lexically processed in parallel. All of the words that are processed in parallel have an activation level, with this increasing during the early stages of lexical processing and reducing towards zero as processing is completed. The speed at which activation rises and falls is influenced by a word's difficulty, as determined by frequency and predictability. The next fixation location is determined by which word in the perceptual span is most activated when the random timer for the current fixation reaches zero. At times, this can be the currently fixated word as opposed to one in the parafovea, leading to a refixation on the same word. This set of parameters allows SWIFT to explain parafoveal-on-foveal effects. Essentially, the difficulty of processing a parafoveal word influences its activation level when the random timer reaches

zero, which in turn influences whether the next fixation is directed towards a parafoveal word rather than word n . The activation of word $n+1$ will be relatively low when this word is hard to process, increasing the probability for a re-fixation on word n . Obviously, whether or not word n receives a further fixation impacts on the total amount of time that it is fixated, thus explaining parafoveal-on-foveal effects. It is worth noting that this set of parameters does not allow SWIFT to predict parafoveal-on-foveal effect in single fixation measures. SWIFT does not currently contain any parameters relating to syntactic integration. However, it has been suggested that efforts to model eye movement behaviour may be improved through allowing the surprisal metric, which can be considered a measure of sentence processing difficulty, to influence processing in a similar way to frequency and predictability (Boston, Hale, Kliegl, Patil, & Vasishth, 2008).

Relative clause processing

In the current study we were interested in testing whether readers are able to detect a capitalised proper noun in the parafovea, and thus potentially attempt to integrate this noun into a syntactic structure sooner than is typical, leading to a parafoveal-on-foveal effect. To this end, we presented participants with sentences including subject relative clauses (SRCs; e.g., *The tall lanky guard who alerted Charlie to the danger was young*) and sentences containing object relative clauses (ORCs; e.g., *The tall lanky guard who Charlie alerted to the danger was young*), with the relative clause noun always being a proper noun. The difference in the ordering of the noun phrase and verb phrase between these two structures has implications for the way in which readers must interpret these sentences. Both structures contain a gap, into which readers must integrate the main clause noun (*the guard*, in the current example). However, the position of this gap varies between SRCs and ORCs. In SRCs the gap is immediately before the relative clause verb *alerted*, meaning that readers must co-index this gap with the main clause subject (e.g., *the guard alerted Charlie*). In

ORCs the gap immediately follows the verb *alerted*, meaning that readers must co-index the relative clause object with the main clause subject (e.g., *Charlie alerted the guard*).

A large body of research has demonstrated that readers have greater difficulty processing ORCs than SRCs, with this processing difficulty affecting patterns of eye movements during reading (Gordon, Hendrick, Johnson, & Lee, 2006; Staub, 2010; Traxler, Morris, & Seely, 2002; Traxler, Williams, Blozis, & Morris, 2005). Of particular interest for the current study is that these effects occur fairly rapidly, with Staub (2010) finding that fixation times and regression probabilities increased in ORCs as early as the word *the* for relative clauses including common nouns (e.g., *the reporter that the senator attacked/attacked the senator admitted the error*), at the left edge of the relative clause, with this determiner signalling that the relative clause starts with a noun phrase as opposed to a verb phrase. We will defer discussing theoretical accounts of the cause of these processing difficulties until our general discussion. For now, it is enough to know that these two structures are ideal for testing whether readers do experience parafoveal-on-foveal effects as a result of detecting a capitalised proper noun in the parafovea, since if they do attempt to integrate this into the syntactic structure the relative clause effect should occur while they are still fixated prior to the relative clause.

The current study

In the current paper we present participants with sentences containing ORCs and SRCs in order to determine whether readers experience syntactic parafoveal-on-foveal effects when a low-level cue can be used to infer that an upcoming word is a noun, when a noun in this position would make the sentence difficult to process. Specifically, we present participants with sentences including relative clauses with capitalised proper nouns. However, unlike previous researchers, we set out to investigate whether an effect of clause

type is present earlier in the sentence, during fixations on a pre-target region, rather than on the relative clause itself. To this end, we also ensured that the noun and verb in our relative clause were matched for orthographic frequency in order to avoid an effect similar to that observed by White (2008) which could interfere with any syntactically based effects. We also matched these words for length, in order to avoid observing parafoveal-on-foveal effects caused by inflated fixations prior to the skipping of a word (see Kliegl & Engbert, 2005).¹ In addition to our two basic conditions, we included various control conditions across different experiments in order to assess the extent to which any effects were influenced by the presence of a capital letter in the parafovea as opposed to the lexical parafoveal processing of the words forming the relative clause.

As well as having implications for the way in which people process parafoveal information, a parafoveal-on-foveal effect in our study may have implications for theories of relative clause processing which we will discuss in our General Discussion, and also indicate that readers use low-level visual information in the parafovea to make representational inferences about higher-level information like syntactic structure. This would be consistent with a recent theory proposed by Martin (2016). This theory attempts to account for language processing in a way that is neurologically plausible, and using psychophysiological mechanisms that have been established in research on perception. Martin posits that language processing functions as a form of hierarchical cue integration, whereby lower level representations cue activation of higher level representations (e.g., features cue letters, which cue bigrams, which cue words, which cue certain syntactic structures etc.) in a form of perceptual inference, while these high-level representations can also increase activation of lower level representations. The extent to which a particular representation will act as a cue for a representation of a different level is determined by how reliably that representation has previously been predictive of the representation of another level. An ORC representation

would typically be cued by input at the word level which is consistent with this structure, with the ORC effect occurring once the relative clause noun has been processed to the point that syntactic class has been determined. The presence of a capital letter at the beginning of this word would act as a highly reliable cue that this word is a noun, and thus as a cue for the ORC; furthermore, it would allow the language processor to cue this syntactic structure more rapidly, prior to the lexical processing of the relative clause noun. Thus, any effect of the manipulation in our experiment during fixations on a pre-target region could be taken as evidence that readers make use of lower-level cues to trigger higher-level representations.

Experiment 1

In Experiment 1 we presented participants with sentences containing either an SRC or ORC, and varied whether these items were presented in normal sentence casing, or entirely in upper case. In the sentences in normal casing the capital letter at the start of the relative clause noun will provide participants with a cue that they are likely to encounter an ORC while still fixated prior to the relative clause. Consequently, we may observe inflated reading times on the word *who*. In contrast, in the upper case sentences there was no diagnostic parafoveal cue (in the form of an initial capital letter) that an upcoming word was a noun, with prior research suggesting this word should not be parafoveally identified as a noun via lexical processing; in these sentences we predicted no differences between sentences including ORCs and SRCs in the pre-target region, although we did predict these effects in fixation times on the relative clause itself, consistent with prior research.

Method.

Participants. 40 native speakers of English from the University of Edinburgh community with normal or corrected to normal vision participated for £6. 16 additional participants were tested but excluded due to a high level of tracker loss.²

Apparatus. Eye movements were tracked using a tower-mounted SR Research Eyelink 1000. Sentences were displayed on a single line. Viewing distance was 70cm, with 1° of visual angle containing 2.7 characters of courier new font.

Materials and design. Sixty-four pairs of sentences containing either an SRC or ORC were designed for this study (see Supplemental Materials for a complete list), and were presented in the following four conditions:

SRC, normal case:

The tall lanky guard who alerted Charlie to the danger was young.

ORC, normal case:

The tall lanky guard who Charlie alerted to the danger was young.

SRC, upper case:

THE TALL LANKY GUARD WHO ALERTED CHARLIE TO THE DANGER WAS YOUNG.

ORC, upper case:

THE TALL LANKY GUARD WHO CHARLIE ALERTED TO THE DANGER WAS YOUNG.

The overt argument of the relative clause verb always consisted of a proper noun. The critical noun and verb in our relative clauses were matched for mean log bi- and trigram frequencies (retrieved using N-Watch; Davis, 2005) and initial trigram frequencies (retrieved using CELEX's word form corpus). Paired t-tests confirmed that there were no differences in

mean log bigram frequency ($t(63)=-0.27$, $p = 0.79$; verb mean = 2.56 , noun mean = 2.58), mean log trigram frequency ($t(63)=1.09$, $p = 0.28$; verb mean = 1.60, noun mean = 1.50), or log initial trigram frequency per million ($t(63)=-0.04$, $p = 0.97$; verb mean = 1.84 , noun mean = 1.85). These controls were undertaken to avoid the chance of observing a parafoveal-on-foveal effect driven by the orthographic familiarity of the parafoveal word (e.g., White, 2008) as opposed to relative clause type. In addition, we matched for length on a by-item basis (mean length = 6.45). These items were presented alongside 64 filler sentences within a Latin-square design. The filler items were all syntactically simple sentences.

Procedure. Upon arrival participants were given information and consent forms. Readers' heads were stabilized using a head and chin rest. A three-point horizontal calibration grid was used, with the calibration being accepted if average error was below 0.30 degrees. Each trial was preceded by a drift check in the centre of the screen, followed by a drift check on the left of the screen, followed by a gaze contingent box in the same position as the first character of the sentence. Participants were recalibrated if either drift check returned a value greater than 0.40 on two consecutive trials or they failed to trigger the gaze contingent box. Participants pressed a button once they had read each item. Yes/no comprehension questions were presented following one third of the sentences, and participants answered using the left or right mouse button. Comprehension questions were distributed evenly among the experimental items and filler items, and did not explicitly probe whether readers had correctly parsed the relative clause. The experiment took approximately 25 minutes to complete. Ethical approval was received from the University of Edinburgh's Philosophy, Psychology, and Language Sciences Research Ethics Committee.

Results.

Participants answered 96% of comprehension questions correctly. Prior to analysis of reading data we 1) removed fixations above 800ms; 2) merged fixations below 80ms with fixations less than 0.5 degrees of visual angle away; and 3) merged fixations below 40ms with fixations less than 1.25 degrees away. Trials in which participants blinked while fixated on an interest area were not included in the analysis of that interest area. This accounted for 1.9% of fixations in the pre-target region and 3.4% in the relative clause region. For each measure, we removed observations more than three standard deviations from the grand mean. This accounted for a maximum of 2.1% of data in an interest area.

We analysed reading behaviour across two interest areas. The first consisted of the relativizer *who* and the space preceding it.³ In this region we examined gaze durations (i.e., the summed fixation duration between first fixating a region and making a saccade to another region), go-past time (i.e., the summed fixation duration between first fixating a region and making a progressive saccade beyond it), last fixation durations (i.e., the duration of the last fixation in the region), and skipping probability (i.e., the probability of readers not directly fixating *who* in first-pass reading). We also analysed reading of a region consisting of the relative verb and proper name in the relative clause (e.g., *Charlie alerted/alerted Charlie* in the above example item) and any intervening prepositions (e.g., *sunbathed with Charlotte/Charlotte sunbathed with* in the sentence *The thin blonde girl who sunbathed with Charlotte/Charlotte sunbathed with was already tanned*), examining first pass time (equivalent to gaze duration, but used for multi-word regions), go-past time, total reading time (i.e., the total time spent fixating in the region), and the probability of making a first pass regression out of the region. Finally, we analysed reading time across our entire sentences in order to assess the extent of any relative clause effects regardless of which region they appeared in. For all reading time measures any values more than three standard

deviations from the mean were removed, and log-transformed values were used in our analysis due to this increasing normality.⁴

We constructed linear mixed-models using the lme4 package (Bates, Maechler, Bolker, & Walker, 2015) in R (2017) to assess the effect of our manipulation. Data files and analysis scripts are available online at <https://osf.io/ep7yd/>. Our primary model consisted of main effects of relative clause type and sentence casing, as well as an interaction between these two factors. In cases where we either observed a main effect of relative clause type or an interaction between clause type and sentence casing we ran an additional LMM with contrasts assessing 1) whether there was a simple effect of clause type for sentences in normal casing and 2) whether there was a simple effect of clause type for sentences presented in upper case. All models included random intercepts for subjects and items, and random slopes where possible. If a model failed to converge with a full random structure, slopes were first removed for items. The final structure for each individual model can be seen in the R Scripts provided online. Estimated means from the models for each condition are presented in Table 1,⁵ while the output for the models examining reading behaviour on *who* are presented in Table 2 and the output for models examining reading behaviour on the relative clause itself and whole sentence are presented in Table 3. An effect was treated as significant with a *t*-value of above 1.96.

Pre-target region *who*. There were significant main effects of both clause type and capitalization in gaze duration and go-past time, as well as a significant interaction between these two factors. Our simple effects contrasts revealed that in normally cased sentences there was a significant clause type effect, such that gaze durations were 20ms longer when *who* was followed by an ORC, while go-past times were 34ms longer. There was no effect of clause type in sentences displayed entirely in upper case. In word skipping there was no effect of clause type, and no interaction between sentence casing and clause type. There was

a marginal effect of casing, such that participants were less likely to skip *who* when it was presented entirely in upper case.

In our model for last fixation duration we also examined whether fixation location interacted with the effect of our other variables. The inclusion of fixation location may be advantageous, since it allows us to assess whether any effects were purely driven by fixations on the final characters of *who*, and thus the extent to which our effects could be driven by mislocated fixations as opposed to parafoveal processing (see Drieghe et al, 2008). In order to assess this possibility we first constructed a basic model including just our independent variables and their interaction. We used the `anova()` function in R to compare the fit of this model to more complex models including fixation location as 1) a main linear effect, 2) a main quadratic and linear effect, 3) a main linear effect interacting with clause type, and 4) a main linear effect and part of a three-way interaction with clause type and sentence casing. The most complex model which had a significantly better fit to the data than simpler models included distance as a main linear effect, with no interactions. The estimated means from this model are presented in Table 1. The model predicted significant effects of clause type and location, and a significant two-way interaction between clause type and sentence casing. Our simple effects contrasts demonstrated that participants' last fixation on *who* was 21ms longer when it was followed by an ORC in sentences in normal casing, while this effect was not observed for sentences written entirely in upper case. The fact that allowing fixation location to interact with clause type as part of either a two- or three-way interaction did not improve the fit of our model to the data suggests that this effect was not primarily driven by mislocated fixations on the final character of *who*.⁶

Relative clause. We observed significant main effects of clause type and capitalization, as well as an interaction between these factors, in all reading time measures. First pass times were significantly shorter in the ORC than SRC for sentences written in

normal casing (a 62ms difference), with a non-significant trend in the opposite direction for upper case sentences (13ms). In upper case sentences, go-past times were significantly shorter in SRCs than ORCs by 38ms, with a non-significant 7ms trend in the opposite direction for normal sentences. Total reading times were significantly shorter in SRCs than ORCs by 83ms in upper case sentences, with a non-significant 9ms trend in the same direction for normal sentences. We also examined the probability of making a first pass regression out of this region, and found a significant effect of clause type, but no effect of capitalization or interaction. Participants were more likely to regress from an ORC than SRC, with both contrasts in our additional LMM showing significant effects in this measure (an effect of 0.10 in normal sentences, and 0.05 in upper case sentences). These regressions were presumably made more rapidly in sentences written in normal casing, as indicated by the shorter first pass times for ORCs.

Sentence reading times. Finally, we assessed the effect of our manipulation on total sentence reading time. This analysis was performed to ensure that the relative clause effect was significant in both sentence casing conditions, despite appearing in different regions. There were significant main effects of clause type and capitalization, with our additional contrasts confirming that participants spent longer reading ORCs than SRCs in normal sentences (a 170ms effect) and upper case sentences (a 130ms effect).

Discussion

In Experiment 1 we set out to test whether readers are able to detect the capital letter at the start of a parafoveal proper noun, and whether this results in an earlier effect of relative clause type than is observed when such a cue is not available. We presented participants with sentences containing either ORCs or SRCs, written in either normal casing or entirely in upper case. Across whole sentences there were clear relative clause effects in both upper case

and normal sentences, with longer reading times for the ORCs, replicating many previous studies. However, these effects emerged at different points in our two different sentence types. In our upper case sentences—in which there was no parafoveal cue for the syntactic class of the word following the relativizer—these effects primarily appeared during fixations on the relative clause itself, consistent with prior research using common as opposed to proper nouns (e.g., Staub, 2010; Traxler, Morris, & Seely, 2002). In contrast, in the normal sentences, relative clause effects primarily appeared during fixations on the words immediately preceding the relative clause. Thus, we observed what we consider to be a syntactic parafoveal-on-foveal effect, with this effect being driven by a strong orthographic cue.

Our findings with regard to the effect of capitalisation on reading times differ to some prior investigations of this phenomenon (Tinker & Paterson, 1939; White & Liversedge, 2006). The reading times for our whole sentence were 6.6% longer when they were presented entirely in capital letters as opposed to in normal sentence casing, with this difference in reading times being significant. This finding would seem to contradict those of a prior study by White and Liversedge (2006), which found only a 2% increase in reading times for sentences written entirely in upper case, with this effect being non-significant in both a by-items and by-subject analysis. Our findings are more in line with those of Tinker and Paterson (1939) who, similarly to us, found a reliable 7% increase in reading times for sentences written in upper case. White and Liversedge (2006) explained the discrepancy between their findings and those of Tinker and Paterson (1939) as being due to presentation conditions; in Tinker and Paterson's experiment upper case text was larger than normally cased text, while in White and Liversedge's study the two casing types were matched on size. This same argument cannot explain why our findings are more in line with the Tinker and Paterson study than the Liversedge and White study, with upper and normally cased

sentences being matched for the visual extent of characters in our own study. We suspect the difference can most likely be attributed to the difference in the sentences used in each study. The sentences used by White and Liversedge had fairly simple syntactic structures and, most importantly, did not typically include proper nouns which could assist in the parsing of these sentences. As such, in White and Liversedge's study, readers were not deprived of useful information when sentences were presented entirely in upper case as opposed to mixed case, and consequently this did not disrupt reading. In contrast, in our study, readers did lose an important cue to syntactic class and structure when sentences were presented in upper case. A counter-argument to this point could be that this would not explain the increase in reading times for SRC sentences presented in upper rather than normal case. However, this would assume that just because SRCs are easy to process relative to ORCs, they are not at all difficult to process. This is not necessarily the case, with SRCs still requiring participants to resolve a filler-gap dependency.

Experiment 2

There are two potential mechanisms by which the capitalization of the proper noun may be aiding the identification of this word as a noun during fixations on pre-target words, with these mechanisms differing in the extent to which they are compatible with different models of eye movement control. The simplest account involves the capital letter itself identifying the word as a noun, with little need for lexical processing. Under this account, our findings are compatible with both E-Z Reader and SWIFT's approaches to lexical processing. Within E-Z Reader the capital letter may be detected during the pre-attentive visual processing stage which has previously been posited as an explanation for orthographic parafoveal-on-foveal effects. Within SWIFT, the capital letter would be detected during the parallel processing of parafoveal words which occurs as a matter of course. Alternatively, it may be the case that the capital letter drew attention towards the parafoveal noun, leading to

participants lexically processing this word to a greater extent than usual, and thus the early retrieval of its syntactic class. Under this account, our findings would not be compatible with E-Z Reader, since participants would be lexically processing multiple words in parallel. Obviously, this would be considerably less problematic for SWIFT. In order to discriminate between these two possibilities, and to replicate our original findings, we conducted Experiment 2.

In Experiment 2 we set out to further examine the extent to which the parafoveal-on-foveal effects observed in Experiment 1 were due to readers making use of a capital letter in the parafovea to infer syntactic class, as opposed to lexically processing a parafoveal word to the extent that syntactic class was retrieved prior to a saccade being programmed away from the pre-target region. In order to test this we used the boundary paradigm to manipulate whether participants had a valid preview of the relative clause noun and verb prior to making a fixation beyond the word *who*. The following example shows the four conditions, with the preview underlined. The preview changed to the correct text at the point where the reader's gaze crossed an invisible boundary immediately before the space after *who*.

SRC, valid preview:

The tall lanky guard who alerted Charlie to the danger was young.

ORC, valid preview:

The tall lanky guard who Charlie alerted to the danger was young.

SRC, invalid preview:

The tall lanky guard who artinal Cansile to the danger was young.

ORC, invalid preview:

The tall lanky guard who Cansile artinal to the danger was young.

We hypothesised that if readers identify a parafoveal word as a noun due to the capital letter at the start without any need for lexical processing, then the lexical identity of this word should have little influence on the parafoveal-on-foveal effects we observed in Experiment 1. According to this position we would expect to observe a relative clause driven parafoveal-on-foveal effect in both the valid and invalid preview conditions, such that participants should fixate on the pre-target region for longer in sentences containing object as opposed to subject relative clauses. If, on the other hand, the capital letter in the parafovea was leading to increased lexical processing of the parafoveal word, then we may expect an influence of our preview manipulation on relative clause based parafoveal-on-foveal effects. Presumably, when the capitalised parafoveal noun has been replaced by a pseudoword, any increased lexical processing of this word due to the capitalization will not result in the identification of this word as a noun. As such, we would only expect increased reading times on our pre-target region for object relative clauses when there is a valid preview of the words within the relative clause.

Method

Participants. 48 native speakers of English with normal or corrected to normal vision participated for £6. An additional nine participants were tested, but excluded from the final analysis due to poor tracking or noticing more than three display changes.

Apparatus. The apparatus were identical to Experiment 1. The CRT monitor was running at a refresh rate of 120 hertz, as is typical for studies using the boundary paradigm.

Materials and design. The sixty-four pairs of sentences from Experiment 1 were used in Experiment 2. In half of our items both the relative clause noun and verb were replaced by pseudowords prior to the eye moving beyond the relativizer *who*. We matched the pseudoword previews for the noun and verb on the same characteristics as the actual noun and verb. Paired t-tests confirmed that there were no differences in mean log bigram frequency ($t(63)=-0.03$, $p = 0.97$; verb pseudoword mean = 2.65, noun pseudoword mean = 2.65), mean log trigram frequency ($t(63)=0.41$, $p = 0.68$; verb pseudoword mean = 1.48, noun pseudoword mean = 1.51), or log initial trigram frequency per million ($t(63)=-0.25$, $p = 0.81$; verb pseudoword mean = 9.99, noun pseudoword mean = 9.55). These items were presented alongside 48 filler sentences; these filler sentences all included cataphoric expressions with a proper noun (e.g. *After making himself sick, Alan...*)

Procedure. The procedure was identical to Experiment 1, with the exception of the use of a display change.

Results.

Participants answered 94% of comprehension questions correctly. We cleaned our data in an identical way to Experiment 1, and looked at the same measures of eye movement behaviour across the same regions of interest. Blinks led to the removal of 2.5% of data in the pre-target region and 3.4% in the relative clause region. In addition, for all regions we excluded trials in which the display change triggered early (i.e., prior to fixations on the relative clause). This accounted for the removal of 19% of fixation data on the pre-target region,⁷ and 2% of the fixation data for the relative clause region. For fixations on the relative clause region we also excluded trials in which the display change completed more than 10ms into a fixation, accounting for the removal of 2.5% of the fixation time data. Removing outliers for each measure accounted for the removal of at most 1.8% of fixation data.

Our LMMs included main effects of relative clause type and preview, as well as an interaction between these two factors. These LMMs were once again conducted using log-transformed data. When we either observed a main effect of relative clause type or an interaction between clause type and preview type we ran an additional LMM with contrasts assessing 1) whether there was a simple effect of clause type for sentences including correct parafoveal previews and 2) whether there was a simple effect of clause type for sentences without a valid parafoveal preview. Estimated means from the models for each condition are presented in Table 4, while the output for models examining the reading behaviour of *who* are presented in Table 5 and output for models examining the reading of the relative clause and whole sentence are presented in Table 6.

Pre-target region. There were no significant effects of any of our manipulations in gaze durations or go-past times on *who*, although there was a marginal effect of clause type in gaze duration. Turning to the estimated means from our LMMs, when participants were presented with correct previews of the words within the relative clause they showed almost negligible effects of clause type (6ms in gaze duration, 2ms in go-past time), albeit in the same direction as in Experiment 1. When participants were presented with pseudoword previews of the words within the relative clause, there were slightly larger trends for a parafoveal-on-foveal effect (8ms in gaze duration, 9ms in go-past time). There were main effects of both clause type and preview type upon the skipping of *who*; participants would skip *who* more when it preceded an SRC than an ORC, and when the preview of the relative clause was incorrect. In our simple effects contrasts the skipping effect was significant when participants were given an incorrect preview, but not when they were given a correct preview.

Once again, our model for last fixation duration was improved by the inclusion of fixation location as a main effect, but not as part of an interaction with any of our other variables. Our model for last fixation duration showed significant effects of clause type and

significant effects of fixation location. Simple effects contrasts demonstrated that this effect reached significance for items in which participants received an illegal preview (a 10ms effect), but not when participants received a legal preview (a non-significant 6ms trend).

Relative clause. In first pass times we observed significant main effects of relative clause type, such that first pass times were shorter on ORCs than SRCs. There was no significant main effect of preview type, nor a significant interaction. In go-past time the only significant effect was of preview type, such that participants spent less time in this region given a correct as opposed to incorrect preview of the target words. In total reading times there were significant main effects of both clause type (such that participants read SRCs more quickly than ORCs) and preview type (such that participants read this region more quickly when they had a correct parafoveal preview), but no significant interaction. Finally, the probability of making a first pass regression out of this region was significantly greater when the region consisted of an object relative clause, and when participants had received an incorrect preview of the region.

Sentence reading times. Finally, we assessed the effect of our manipulation on total sentence reading time. There was a significant main effect of clause type such that readers read SRCs more quickly, but no significant effect of preview type nor interaction.

Discussion

In Experiment 2 we set out to replicate and extend our main findings from Experiment 1. We presented participants with sentences containing either an SRC or ORC, and manipulated whether participants were given correct or pseudoword previews of the words in the relative clause. The purpose of the preview manipulation was to examine whether participants need to be able to lexically process the words in the parafovea in order to obtain

a syntactic parafoveal-on-foveal effect. We will first focus upon our attempted replication, and then move on to discuss the effect of our preview manipulation.

The pattern of results in Experiment 2 did not as closely replicate Experiment 1 as we had hoped. In our relative clause region we mostly replicated the results from Experiment 1. First pass times in the relative clause region were once again significantly shorter in ORCs than SRCs, with a non-significant effect in go-past times and total times, and with participants being more likely to make a regression out of the region given an ORC. However, in our pre-target region we only observed non-significant numerical trends of 6ms in gaze duration and 2ms in go-past time (compared to 20ms and 34ms for these measures in Experiment 1). Thus, in these two measures we failed to replicate our original finding. However, in last fixation duration we did observe a main effect of clause type, with participants' final fixations on *who* being longer when it was followed by an ORC.

Given the lack of a full replication of our original finding, assessing the effect of our preview manipulation is not straightforward. Recall that we had two competing hypotheses. According to the first, the effect from Experiment 1 may have been driven purely by a low-level cue (e.g., a capital letter in the parafovea) indicating the syntactic class of a parafoveal word; according to this hypothesis we should have observed equivalent syntactic parafoveal-on-foveal effects regardless of the preview participants received. According to our second hypothesis, the effect from Experiment 1 may have been due to the capital letter resulting in increased lexical processing of the parafoveal noun, leading to it being identified as a noun through lexical identification; this hypothesis would predict that our effect from Experiment 1 would no longer be present when it is not possible to lexically identify the parafoveal word. We observed neither of these patterns of results. Rather, in the current experiment, there was actually a numerically larger parafoveal-on-foveal effect of relative clause type when participants were presented with an incorrect as opposed to correct preview of the parafoveal

words. However, it is also the case that the effect for incorrect previews is numerically smaller than the effect observed for correct previews in Experiment 1. Due to this, we will delay attempting to explain this pattern of results until our General Discussion, once we have further data clarifying the size and reliability of our basic effect.

Experiment 3

The findings from Experiments 1 and 2 leave us with a somewhat unclear and contradictory picture, and unsure whether there even is a parafoveal-on-foveal effect of relative clause type. This is not entirely unexpected. It has recently been argued (e.g., Vasishth, Mertzen, Jäger, & Gelman, 2018) that experiments in psycholinguistics are often underpowered, thus leading to a lack of precision in the estimates of an effect size in any individual experiment. As such, a (significant) effect of 20ms in Experiment 1 and a (non-significant) effect of 6ms in Experiment 2 are not necessarily inconsistent with each other. Rather, they may be a result of two different noisy samples of an underlying real effect.

In order to obtain a more precise estimate of our effect, we conducted a third experiment. In this experiment we simply included the two basic conditions from Experiments 1 and 2 (i.e., participants read sentences containing either an SRC or ORC, with no additional manipulations of sentence casing or preview type). Including only these two conditions allowed us to double the number of experimental items in each condition, thus considerably increasing statistical power. Furthermore, we also increased our participant sample size to 60 (vs. 40 and 48 in Experiments 1 and 2, respectively), again increasing power, and allowing us to obtain a more precise measurement of our effect.

Method

Participants. 60 native speakers of English with normal or corrected to normal vision participated for £6.

Apparatus. The apparatus were identical to Experiment 1 and 2.

Materials and design. The same stimuli were used as in Experiment 1 and 2.

Participants viewed each sentence with either an ORC or SRC, with 32 items presented in each condition. These sentences were intermixed with 78 unrelated fillers. These fillers included 30 sentences with simple syntactic structure in which the indefinite article *an* was followed by a capitalised proper noun, and 48 containing causal dependent clauses (e.g. *Sally frightens Mary because she...*).

Procedure. The procedure was identical to Experiments 1 and 2.

Results

Participants answered 95% of comprehension questions correctly. We cleaned our data in an identical way to Experiment 1 and 2, and looked at the same measures of eye movement behaviour across the same regions of interest. Removing trials including a blink accounted for 2.4% of data in the pre-target region and 3.5% of data in the relative clause region. Removing outliers accounted for at most a further 1.8% of data. In this experiment, our linear mixed models simply consisted of a main effect of relative clause type with an appropriate random structure. Estimated means from the models for each condition are presented in Table 7, while the output for models examining the reading of *who* are presented in Table 8 and models examining the reading of the relative clause and whole sentence are presented in Table 9.

Pre-target region. There were significant effects of clause type in gaze duration and go-past time, with 14ms and 26ms longer reading times in sentences containing ORCs than SRCs. Thus, we replicated the effect from Experiment 1. There was also a significant effect of clause type on the skipping of *who* in this experiment, with participants skipping *who* 6% less when it was followed by an ORC as opposed to an SRC. While this same effect was not

significant in the baseline conditions of Experiment 1 and Experiment 2, there was a trend in this direction in both experiments.

In last fixation durations, a linear effect of fixation location did not improve the fit of our model to the data in this experiment, but a quadratic effect did. This effect of fixation location did not interact with clause type. In this measure there was a 13ms effect of clause type.

Relative clause. We observed significant effects of clause type in first pass times, go-past time, and the probability of participants making a regression, but not in total viewing times. First pass times and go-past times were 67ms and 21ms shorter, respectively, in the ORC than SRCs, with a trend for total reading times to be shorter in SRCs than ORCs. Finally, participants were twice as likely to make a regression out of an ORC (0.14) than an SRC (0.07).

We also used the data from this experiment to test whether our first pass time effect was primarily due to participants making more regressions in ORCs than SRCs, or if readers would still have shorter first pass times on ORCs than SRCs even when they exited both regions to the right after first fixating the region. Contrary to our expectations an ORC advantage was still present and significant ($b=-0.07$, $SE=0.02$, $t=-4.08$) in this subset of trials, such that first pass times were 41ms shorter for ORCs, even when participants did not make a regression out of the region. We will return to this issue in our General Discussion.

Sentence reading times. Participants took significantly longer to read sentences containing ORCs than SRCs, with a sentence reading time difference of 166ms.

Discussion

Having observed a somewhat contradictory pattern of results across Experiment 1 and Experiment 2, we conducted Experiment 3 in order to further assess the effect of our basic

manipulation (i.e., reading sentences containing SRCs vs. reading sentences containing ORCs) with considerably more statistical power, and to obtain a more precise estimate of the size of our effect. The results from this experiment were far more in line with the results from Experiment 1, in that readers took significantly longer to read the pre-target region in all three measures when a sentence contained an ORC as opposed to an SRC.

Composite Bayesian Analysis

Rather than proceeding on the basis that our effect is most likely real and reliable given that we observed it in two out of three experiments, we chose to combine the data for the relative clauses presented under normal conditions (i.e., typical sentence casing and with correct parafoveal previews) from all three of our experiments into a single analysis, with 148 participants. Rather than constructing standard LMMs to analyse this data set, we constructed Bayesian LMMs (see Nicenboim & Vasishth, 2016 for a brief introduction to using Bayesian data analysis in linguistic research) using the BRMS package (Bürkner, 2017) in R. Our main reason for taking this approach is that a Bayesian analysis allows us to quantify the level of uncertainty in our estimates of parameter values, or, in other words, the size of our relative clause effect. This contrasts with a standard frequentist approach, which simply allows us to state that the value of our parameter is significantly different from a null value of 0. Given that the effect of relative clause type varied across experiments, it is worthwhile determining a range of values that we are confident contains our true parameter value. This can be done through Bayesian data analysis by constructing a 95% credible interval, with this representing the range of values that we are 95% certain the true value of a parameter lies.

In each Bayesian LMM we used a prior of $Normal(\mu=0, \sigma=10)$ for the model intercept and $Normal(0, 1)$ for the effect of clause type, with a regularization of 2 on the covariance matrix of random effects. These priors would be considered weakly informative,

given that we are dealing with log-transformed data. The models were run with two chains of 2000 iterations each.

Selected output from our Bayesian analysis is presented in Table 10. This output includes the median estimate of the intercept for each measure, the median estimate of the effect of condition, and both the lower and upper end of the 95% credible interval for this effect. We can be 95% certain that our true parameter value lies within this credible interval. This data suggests that in the pre-target region we can be 95% certain that the effect of relative clause type is at least 8ms in gaze duration and 12ms in go-past time and at most 19ms and 26ms, with the most likely effect size for these two measures being 15ms and 19ms. In last fixation duration the 95% credible interval for the main effect of clause type spread from a 7ms processing cost to a 18ms processing cost, with a median value of 11ms. The size of this effect was uninfluenced by fixation location. Finally, participants were more likely to skip *who* when it preceded an SRC than ORC, with a median estimate of a 3% skipping effect.

In the relative clause region our Bayesian analysis suggested that there was an effect of relative clause type in first pass time, but not in go-past time and total time. In first pass time the lower boundary of the credible interval for our effect was of 51ms shorter first pass times in ORCs, with the most credible effect size being 67ms and the largest credible value being 82ms. In both go-past time and total reading time our 95% credible interval included a reading time difference between our different relative clause types of 0ms; as such, our Bayesian analysis does not allow us to conclude that there was any effect of relative clause type in these measures. Finally, our Bayesian analysis showed that participants were between 3 and 6% more likely to make a regression out of an object relative clause than subject relative clause.

In terms of whole sentence reading time, our Bayesian analysis suggested that participants took between 93 and 190ms longer to read sentences containing object relative clauses compared to those containing subject relative clauses.

Bayesian Analysis of Rayner and Schotter (2014)

As mentioned above, a prior study conducted by Rayner and Schotter (2014) examined the effect of noun capitalization on parafoveal preview benefits. The logic of the current study was in part based on the fact that Rayner and Schotter did not observe a parafoveal-on-foveal effect of proper noun capitalization. However, their study only reported gaze durations on the pre-target word, meaning that it could be the case there was an unreported effect of capitalisation in other measures. If this were the case, it would suggest that our findings had very little to do with capitalisation signalling syntactic class, as opposed to capitalised words simply attracting attention due to visual saliency. In order to assess this possibility, we present a re-analysis of this older data set.

We retrieved Rayner and Schotter's data from the UCSD Keith Rayner Eye Movements in Reading Data Collection (Rayner & Schotter, 2015). This data set included sixty participants and sixty items. We treated this data set as a two condition experiment, with the parafoveal noun being either capitalised or uncapitalised. While Rayner and Schotter (2014) also manipulated the parafoveal preview of this word, we did not treat this as a meaningful variable in the current analysis. This gave us thirty items per condition for each subject, leaving us with a very similar level of power to Experiment 3 of the current paper to detect any effect of proper noun capitalisation. For Gaze Duration, we were able to use Rayner and Schotter's pre-processed data, as this was one of the analyses that they report in the paper. For Go-past and last fixation duration, we needed to use our own scripts on the raw data files, as Rayner and Schotter did not include these measures for the pre-target word⁸.

We analysed this data set in an identical manner to our own composite data set, using Bayesian linear mixed models, with the same priors as set above, and calculated credible intervals. We examined gaze durations, go-past times, and last fixation durations on the word preceding the noun which was either capitalized or uncapitalized. We collapsed our data across the three different preview conditions used by Rayner and Schotter. These credible intervals are presented in Table 10. This analysis provided very little evidence for a parafoveal-on-foveal effect of the capitalisation of an upcoming noun outside of the context of an ORC. In all three measures the credible interval for the effect of capitalization crossed 0. The median estimate of the effect was 4ms in gaze duration, 2ms in go-past time, and 2ms in last fixation duration. On the basis of this analysis it seems fair to conclude that there was no parafoveal-on-foveal effect of capitalization in this prior study.

General Discussion

In the current study we set out to test whether readers are able to detect the capital letter at the start of a parafoveal proper noun in an object relative clause, and whether this results in a parafoveal-on-foveal effect. Across three experiments we presented participants with sentences containing either ORCs or SRCs. We observed clear effects of our basic manipulation, whereby participants had longer gaze durations (a 15ms effect in our composite analysis), go-past times (19ms), and last fixation durations (11ms) on our pre-target region when it was followed by an ORC with a capitalised proper noun as opposed to an SRC. In addition to the parafoveal-on-foveal effect, there were interesting effects (and lack thereof) in our relative clause region. First pass times were 67ms shorter when participants read object- rather than subject-relative clauses, while any differences in go-past time and total reading time were negligible. A lack of increased first-pass reading times in go-past times for ORCs containing a proper noun are consistent with studies of self-paced

reading (e.g. Gordon, Hendrick, & Johnson, 2001). Finally, in sentence reading times there was a 157ms SRC advantage.

In addition to examining our effects in normally presented relative clauses, we also tested the extent to which our basic effects were driven by the availability of a capital letter in the parafovea (Experiment 1) or lexical information in the parafovea (Experiment 2). We precede our discussion of these effects with an acknowledgement that our estimates of the size of the effect under these conditions is considerably more susceptible to sampling error than the estimate of our main effect, and that future studies may be necessary to determine whether the conclusions we draw below are accurate. In the upper case conditions of Experiment 1, participants read sentences in which a capital letter at the start of the word could not indicate syntactic class, due to the entire sentence being entirely written in capital letters. There were two notable effects of this. First of all, the relative clause type no longer influenced fixation durations in the pre-target region. Second, the effect of clause type on fixations in the relative clause region itself was more similar to what has typically been observed in studies using common as opposed to proper nouns, such that first pass times were numerically longer and go-past times and total reading times significantly longer in ORCs than SRCs. Thus, it seems that the capital letter in our normal conditions was allowing participants to infer that they were processing an ORC prior to direct fixation, and that this slowed fixations in the pre-target region, but decreased processing difficulty once they directly fixated the clause. In Experiment 2 readers were deprived of a valid parafoveal preview of the relative clause, and thus any effects could only have been due to readers using a capital letter as a cue to syntactic class. Once again, this data should be interpreted cautiously, due to the null effects in our valid preview condition from this experiment. However, from this experiment it seems fair to at least conclude that our effect is not wholly dependent upon the lexical identification of the parafoveal noun, with a 10ms parafoveal-on-

foveal effect of clause type being present in last fixation durations for relative clauses with a false preview. Thus, together, Experiment 1 and 2 suggest that our effects were more likely to have been driven by proper noun capitalization than by lexical processing of parafoveal words.

Syntactic Structure or Visual Salience?

Throughout this paper so far we have discussed a parafoveal-on-foveal effect of capitalization as being due to this signalling the syntactic class of the upcoming word to readers. There is, of course, a less interesting explanation of our data. Essentially, it may be the case that our effects are simply due to a capital letter being orthographically salient, and thus leading to inflated fixation durations in a similar manner to unusual letter combinations in the parafovea (e.g. White, 2008). Although we acknowledge that this is a possible account of our data, there are a number of reasons we favour a syntactic as opposed to visual-saliency explanation of our effects. First – as shown in the Bayesian analysis above – is the way in which our effects differ from the (lack of) effects in the data of Rayner and Schotter (2014). In this prior study participants read sentences in which the target noun typically appeared in a position where it would not be considered difficult to process in extant theories of sentence processing (see below for an elaboration of such theories). This noun was identical in both the capitalised and non-capitalised conditions. As shown by our reanalysis of this data, whether this parafoveal noun was capitalised or not had very little effect on fixations on the prior word. If the effect of capitalisation observed in our own study was simply due to visual salience then such effects should occur regardless of syntactic structure. This is not to say that the effect should exclusively occur in object relative clauses; rather, a parafoveal-on-foveal effect of noun capitalization may occur in any syntactic structure in which a noun in a certain position should result in processing difficulty, with the relative clauses used in the current study being a strong example of such structures. Future research in this area may be able to

take advantage of this, through testing whether noun capitalization results in parafoveal-on-foveal effects for structures that would be considered difficult to process by different theories of sentence processing.

A second reason for rejecting an explanation of our finding due to visual salience is our skipping data; across all three experiments there was a trend for participants to skip *who* less when it preceded a capitalized word (i.e. an ORC) than an uncapitalized word (i.e. an SRC), and this effect was reliable in our Bayesian analysis. This seems unlikely to occur in a visual-saliency explanation of our effects; rather, if attention was drawn early towards the visually salient information we might expect increased skipping of *who*, with participants' eyes being attracted towards the salient information (see Hyönä, 1995; Radach, Inhoff, Glover, & Vorstius, 2013). We will outline how the skipping effect fits into a syntactic framework further below.

Third, along a similar line, is the way in which our effect grew in go-past time relative to gaze duration. If our effects were exclusively due to attention being drawn towards visually salient information this would seem to make little sense. In order for an effect to grow larger between these two measures, participants must have been re-reading earlier parts of the sentence prior to making a fixation to the right of *who* when this word was followed by an ORC rather than an SRC. Re-reading earlier portions of a sentence would seem to be an irrational response to visual salience to the right of fixation, while it makes sense as a response to syntactic parsing difficulty.

The fourth and final reason we favour a syntactic locus of our effects is the pattern of effects observed in our relative clause region. Recall that within ORCs we should typically expect a syntactically based processing cost upon direct fixation of the relative clause, an effect which was indeed present in our fully capitalized sentences in Experiment 1. If the

parafoveal-on-foveal effect of capitalization was merely an effect of visual salience, independent of syntactic factors, then we should presumably still have observed standard relative clause effects upon participants directly fixating the relative clause itself. However, this was not the case; rather, in our composite analysis the 95% credible interval for the effect of clause type on both go-past times and total reading times on the relative clause region were mostly centred around zero, with a median effect estimate of a 7ms ORC advantage in go-past time and 9ms ORC cost in total reading time. It is our contention that we did not observe standard relative clause effects in the relative clause region due to these effects already having manifested themselves earlier in the sentence as a parafoveal-on-foveal effect.

Due to the reasons outlined above, we view our effect as being more likely to be due to syntactic factors, as opposed to simply visual salience. Nonetheless, before proceeding we will briefly consider the relevance of our findings under a visual salience account and in relation to prior research showing parafoveal-on-foveal effects of unusual orthographic information. As mentioned above, parafoveal-on-foveal effects of orthographically unusual information tend to be limited to the last fixation made prior to the target word (e.g. White, 2008), and, in the case of Drieghe et al. (2008) only when this fixation was made very close to the unusual information. Our effect, on the other hand, was reliable in both gaze duration and go-past times as well as last fixation durations, although this does come with the caveat that our pre-target region was relatively short, and so would have received multiple first-pass fixations relatively rarely. Thus, even if our effect is due simply to visual salience it still represents an advance on previously observed parafoveal-on-foveal effects. Furthermore, our effect could also be considered an advance on these effects, since they are due to the typographical characteristics of a single letter, as opposed to how often a series of letters appear together. Further research may be needed to fully understand the locus of our effect, regardless of whether it is due to syntactic factors or visual salience. For example, even in a

visual salience account there must be some factor which led to a difference between our own findings and those of Rayner and Schotter (2014) — future work focusing on factors that differ between their stimuli and our own beyond syntactic complexity may be necessary to fully determine what drives the effects of capitalisation observed in the current study. One possibility is that our use of a shorter word preceding the capitalized noun played a role, such that the lower processing load of *who* resulted in participants extracting information from the capitalized noun earlier than in Rayner and Schotter's study.

Visual cues for syntactic class

Our study contributes to a growing literature examining syntactic processing in the parafovea (Brothers & Traxler, 2016; Snell, Meeter & Grainger, 2017; Veldre & Andrews, 2018). These prior studies have demonstrated that readers process syntactic class in the parafovea to the extent that previews which are syntactically invalid continuations of a sentence are skipped less, and result in longer fixation durations on a syntactically legal target word. However, none of these prior English studies observed parafoveal-on-foveal effects, despite including syntactic manipulations that were more extreme than in the current study (i.e., violations as opposed to a difficult structure). Thus, our study extends the existing literature by demonstrating very early processing of syntactic information in the parafovea in English. This early effect was most likely driven by the capitalization of our parafoveal noun allowing readers to retrieve syntactic class prior to lexical processing.

The fact that our effect seems to have been driven by an interaction between low-level visual information (i.e., proper noun capitalization) and high-level syntactic information (i.e., the fact that a noun in a certain position makes the sentence difficult to process) has implications for various theoretical positions on language processing and reading. At a broad level, it suggests that when constructing a syntactic structure, the parser is capable of

incorporating elements on the basis of only a knowledge of the syntactic class of that word, in the absence of any semantic knowledge about the identity of that word. This interaction of a cue to syntactic class with syntactic structure also lends support to Martin's (2016) theory of language processing discussed above. Within this theory lower level cues activate higher level representations, with a capital letter at the start of a word being a highly reliable cue of syntactic class, with this in turn cueing a difficult syntactic structure.

In terms of visual cues for syntactic class, a capital letter at the start of a word is a very reliable cue that a word is a noun. Other visual cues may also be informative of syntactic class, albeit in a far less reliable manner. For example, Farmer, Christiansen and Monaghan (2006) demonstrated that verbs tend to be more phonologically similar to other verbs than to nouns, while nouns tend to be more phonologically similar to other nouns than to verbs. This tendency for words of a certain syntactic class to be phonologically similar to each other may also affect the orthographic typicality of these syntactic classes (Tanenhaus & Hare, 2007),⁹ meaning that readers could feasibly use this form typicality to identify a word's syntactic class on the basis of a coarse perceptual analysis rather than through lexical identification. Evidence exists for such an effect from studies using MEG imaging (Dikker, Rabagliati, Farmer, & Pylkkänen, 2010, but see Nieuwland, *in press*), self-paced reading (Farmer et al., 2006), and eye-tracking (Farmer, Yan, Bicknell, & Tanenhaus, 2015), although these effects are not always reliably observed across studies (e.g., see Staub, Grant, Clifton, & Rayner, 2009, who failed to find effects in eye-tracking or self-paced reading). The manipulation in the current study could be viewed as a particularly strong form of typicality, resulting in syntactic class being determined quickly enough to affect fixations even on a pre-target word. It is also worth noting that capitalisation may vary in terms of how diagnostic it is as a syntactic cue across languages. As mentioned above, in German all nouns are capitalised. This means that as well as an upcoming word being capitalised allowing readers to infer that

it is a noun (as in English), an upcoming word not being capitalised may also allow readers to infer that it is not a noun.

Models of eye movement control

Our findings also have implications for models of eye movement control. At a minimum, our study, alongside others of parafoveal syntactic processing, highlight the need for an update of current models of eye-movement control during reading to include some information about syntactic category, structure-building, and natural-language processing metrics like Surprisal. Without a deeper theory of how sentence processing should impact on eye movement behaviour, it is hard to be sure how well either a serial processing model of eye-movement control such as E-Z Reader (Reichle, Warren, & McConnell, 2009) or a parallel processing model such as SWIFT (Engbert, Nuthmann, Richter, & Kliegl, 2005) is able to account for the existence of a syntactic parafoveal-on-foveal effect. Our data does not contradict the idea that lexical processing occurs in a serial manner, given that our effect was driven by a perceptual cue as opposed to lexical processing of the parafoveal word. However, it does at least suggest that salient visual information in the parafovea can affect eye movements through linguistic mechanisms, rather than simply by drawing attention away from the fixated word. Researchers have sometimes argued (e.g., Cutter, Drieghe, & Liversedge, 2017; Reichle, Pollatsek, & Rayner, 2006) that orthographic parafoveal-on-foveal effects are merely the result of unusual visual information popping-out from the page, with actual language processing playing very little role in the effect. The same argument cannot be made to account for the data from the current study, with our effect relying on what a visual cue signals about syntactic class and structure, as opposed to simply being salient.

We will now consider the mechanism through which our manipulation may have affected fixation durations and word skipping on *who*, within the context of models of eye

movement control. We will mainly focus on E-Z Reader, since this model does at least make rudimentary assumptions about how syntactic processing difficulty may affect eye movement behaviour. Briefer consideration will be given to the SWIFT model. Within the E-Z Reader framework, a saccade would have begun to be programmed away from *who* once the L₁ stage of lexical processing had been completed on the relativizer *who*. In cases where L₁ was completed for *who* while participants were still fixated on the previous word (e.g. *guard*), a saccade to skip *who* would have been programmed. While this saccade was being programmed, the L₂ stage of lexical processing would take place on *who*, and upon this word being identified it would have been integrated into the sentential framework while attention shifted to word $n+1$. Upon attention shifting to word $n+1$, its syntactic class would become rapidly apparent due to the capital letter at its start, with this leading to the noun being integrated into the sentential structure, and hence syntactic processing difficulty. In cases when the saccade away from the pre-target region was still in a labile stage this may have resulted in the saccade being cancelled and a further fixation being made upon the pre-target region or at an earlier point in the sentence, leading to inflated first-pass reading times on this region and an even larger effect in go-past times. This would also explain the reduced skipping of *who* in object relative clauses, with saccades which were originally supposed to skip this word being cancelled upon syntactic processing difficulty becoming apparent. One question that arises from this explanation is whether a saccade programme would remain in the labile stage for long enough for these other processes to complete on time. Within E-Z Reader a saccade remains labile for an average of 125ms, while on average the other processes combined should take 97ms. Due to the variation in the duration of these processes the saccade would have sometimes reached a non-labile stage by the time the other processes completed, but on the majority of trials (approximately 82%) the saccade would still have been labile.¹⁰ Thus, it seems that E-Z Reader can indeed account for our findings, assuming

that a word's syntactic class can be determined via a low-level visual cue prior to lexical processing completing. Furthermore, the identification of the parafoveal word as a proper noun on the basis of capitalization would not even need to have occurred overly rapidly. For example, had this process taken a further 28ms on each trial the saccade would still have been in a labile state on approximately 50% of trials, and even a process lasting 48ms would have led to the saccade being in a labile stage on 25% of trials. More sophisticated modelling efforts with E-Z Reader may be necessary to determine how long this process would have needed to last in order to simulate an effect of the size we observed. It is also worth noting that in some trials subjects may have fixated on *who* due to saccadic targeting error when they were actually trying to fixate the following word, resulting in participants having an even greater chance to have shifted attention to the relative clause noun while being fixated on *who*, with this giving them a greater chance to pick up on the low-level cue to syntactic class.

Within SWIFT, once *who* had been fully processed and integrated into the sentence frame, this word should presumably have had zero activation as a potential saccade target. Consequently, by the time it was possible for the relative clause type to influence processing there should have been no way in which fixation times on *who* could be extended, either through further inhibition of the random timer, or through the probability of further fixations being made on this pre-target region. As such, SWIFT may need to take more account of sentence processing mechanisms in order to explain our effects.

Implications for theories of relative clause processing

Finally, it is worth considering whether our effects, when viewed in terms of E-Z Reader as outlined above, have implications for theories that attempt to explain why ORCs are difficult to process. One theory addressing this issue was proposed by Traxler, Williams,

Blozis, and Morris (2005). They proposed that readers use an active filler strategy when processing relative clauses, such that when it becomes apparent that they are processing a structure involving a gap (i.e., upon identification of the relativizer *that* or *who*) they will instantly assume that the gap appears in the subject as opposed to object position, and fill this gap with the main clause noun. When participants are reading an SRC, this processing strategy leads to the correct interpretation of the sentence, and thus it is not necessary for participants to revise their interpretation of the sentence upon processing the relative clause. In contrast, when the sentence contains an ORC, this interpretation of the sentence is erroneous, and the presence of a noun phrase immediately after the relativizer makes it necessary for readers to abandon this interpretation and begin constructing an alternative. It is due to this that readers take longer to read sentences containing ORCs than SRCs. In our experiments, the fact that the relative clause began with a noun would have become apparent soon after the integration of the relativizer, as attention shifted to the parafoveal word with the eye still on the relativizer; this would have resulted in processing difficulty emerging during fixations on the pre-target region.

While Traxler et al.'s theory can explain our finding in the E-Z Reader framework outlined above, it is briefly worth exploring an alternative scenario, in which this theory would have more trouble explaining our findings. Arguably, the capital letter at the start of the parafoveal word may have been salient enough for readers to detect that this word was a noun prior to attention shifting to this word. If this was the case, it would make little sense for readers to integrate the main clause noun into the subject position upon identifying the relativizer, and thus for processing difficulty to occur. Thus, while in our preferred interpretation of our findings this theory can explain our effects well, there are other feasible scenarios which may be more problematic for an active filler approach.

An alternative theoretical position suggests that ORC processing difficulty is driven by working memory processes (Gibson, 1998; Gordon, Hendrick, & Johnson, 2001). This class of theories propose that a large amount of the processing difficulty in ORCs is due to readers having to encode and store multiple noun phrases into memory simultaneously until encountering the relative clause verb in ORCs; in SRCs the relative clause verb precedes the noun, meaning that the main clause noun can be integrated with this verb prior to readers needing to encode the second noun into memory. Our main finding of a parafoveal-on-foveal effect of relative clause type may be well-explained by aspects of memory-based theories. Specifically, the idea that encoding multiple noun phrases simultaneously may be cognitively costly could explain our effects. Here, the capitalised noun in the parafovea acts as a cue that participants need to encode a second noun phrase into working memory while still holding the main clause noun in memory, leading to processing difficulty. We suspect that the extra time spent fixated in the pre-target region is used to more strongly encode the first noun phrase prior to the eye moving onto the second noun phrase and readers beginning to fully encode this word. It should be noted that some memory-based theories (e.g. Gibson, 1998) do not actually include an encoding mechanism, and these theories are unlikely to be able to account for our findings.

There is an aspect of our data which is more problematic for certain memory-based theories. Various studies have shown that when the noun in a relative clause is of a different type (e.g., proper noun) to the main clause noun (e.g., common noun), processing difficulty is reduced, with Gordon et al. explaining this in terms of less similar nouns resulting in less interference (see Gordon et al., 2001). Our data, on the other hand, suggests an alternative explanation of these findings. Essentially, these prior findings may be due to proper noun capitalization, with Experiment 1 in the current study showing effects in the relative clause region more similar to those typically observed for two common nouns when our sentences

were presented entirely in upper case. Future work may need to directly test whether proper nouns and common nouns result in different relative clause effects when proper noun capitalization is removed as a useful perceptual cue.

A final mechanism that has been used to explain ORC processing difficulty is the idea of violated expectations (Levy, 2008; Lewis & Vasishth, 2005). Lewis and Vasishth (2005) proposed a model which primarily predicts reading times on the basis of memory-based mechanisms, but also implements the idea of a left-corner parser which predicts upcoming syntactic constituents on the basis of grammar rewrite rules. Due to this left-corner parsing strategy, the model predicts a verb following a relativizer, meaning that encountering a noun in the ORC leads to inflated reading times, as has been demonstrated from simulations using this model (see Staub, 2010, Footnote 1, page 74). As such, while this is a memory-based model, it accounts for early relative clause effects via an expectation-based mechanism. While Lewis and Vasishth's model includes an expectation-based mechanism, other researchers attempt to predict reading times exclusively on the basis of expectation, which can be operationalized using the Surprisal metric (Hale, 2001; Levy, 2008). These researchers claim that as a sentence is processed, readers construct a probability distribution of all possible sentence structures that are consistent with the current linguistic input and the language's grammar. The probability distribution takes into account the relative likelihood of each structure within the language, such that frequently occurring structures are assigned greater probabilities than infrequently occurring structures. Furthermore, the distribution is constructed and re-calculated incrementally, such that with each new piece of linguistic input (which, for present purposes we assume to be a word) the distribution is altered, with some structures being ruled out, or changing in probability. The degree of update in the probability distribution is predictive of the processing difficulty of each word in the sentence, with words that necessitate a larger shift in the distribution being more difficult to process. Due to

sentences containing ORCs being less common than sentences containing SRCs (Roland, Dick, & Elman, 2007), readers must update this distribution to a greater extent when reading ORCs, thus explaining longer reading times in these sentences. These approaches can explain our findings in a relatively simple manner, whereby the violation of expectations occurs while readers are still fixated on the pre-target region, thus leading to inflated fixation durations here, rather than on the relative clause noun phrase itself. These approaches may also be better able to explain another aspect of our findings than alternative theories. Recall that we observed shorter first pass times in the relative clause region for an ORC than SRC, with Experiment 3 confirming that this effect was not confined to trials in which participants made a regression back to earlier parts of the sentence. Within a surprisal framework this effect could be explained by readers updating their sentence representation to definitely contain an ORC rather than SRC while still fixated in the pre-target region, while in the SRCs they may be unable to update their sentence representation to definitely contain an SRC rather than ORC until direct fixation inside the relative clause. Thus, there is some processing effort needed while fixating the relative clauses for SRCs which is not performed for ORCs earlier in the sentence.

In summary, we set out to investigate whether readers are able to detect proper noun capitalization in the parafovea, and consequently update their sentential representation prior to directly fixating a relative clause. Inflated fixation times on the pre-target region for ORCs suggests that readers are indeed able to do this. These findings have implications both for the way that readers update their sentential representations during reading, and for models of eye movement control.

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Footnotes

¹ Neither of these factors have been properly controlled for in prior studies of relative clause processing using proper nouns. Furthermore, in prior unpublished work conducted by Sturt and Martin, which observed similar effects to those observed in the current paper, these variables were left uncontrolled.

² The cause of this unusually high level of tracker loss was most likely due to an air conditioning unit blowing cold air into subjects' eyes, resulting in a high level of blinking and thus tracker loss. This air conditioning unit was turned off during subsequent testing sessions.

³ We originally tested parafoveal-on-foveal effects of our manipulation on a two-word region consisting of *who* and the prior noun. We used this two-word region for assessing parafoveal-on-foveal effects due to the high skipping rate of the relativizer *who*. However, due to reviewer feedback we switched to using the smaller region. Our original analysis is included in the supplementary materials. It is worth noting that the majority of our effects were also robust in this larger pre-target region which included far more trials than the smaller pre-target region, with the numerical differences between conditions remaining about the same size. Thus, it is not the case that our effects only relate to a small proportion of the sentences participants read.

⁴ An analysis using untransformed reading times can be found in the supplementary materials.

⁵ Tables of means calculated on the basis of the untransformed observed data rather than model estimates can be found in the supplementary materials. We report model estimates in the main paper due to these better accounting for between-subject and between-item noise than raw means.

⁶ Upon suggestion by a reviewer we examined whether the effects in this region were in any way influenced by trial order in each of the three experiments reported in the current

manuscript. This analysis revealed very little systematic variance due to trial order; while allowing trial order to interact with clause type in Experiment 1 in gaze duration improved this fit of our model to the data (with the effect growing smaller throughout the experiment) this effect did not appear in any other measures or experiments. As such, we do not discuss it in-depth.

⁷ This may seem like an unusually high amount of data to lose to early display changes. Indeed, it may even lead some readers to question whether we competently programmed our experiment. However, this high proportion is actually more the product of how regularly “who” was skipped meaning that a relatively small number of display change errors (247 out of 3072 trials) accounted for a large proportion of the trials on which participants actually fixated the pre-boundary word. This is reflected by how little of the data from the relative clause itself was excluded due to this criteria.

⁸ The dataset was missing one of the sixty raw data files that had contributed to Rayner and Schotter’s analyses. Thus, our analyses of Go-past and Last fixation are based on 59 participants, while Gaze duration is based on the full set of 60 participants.

⁹ It is worth noting that the original Farmer et al. form typicality study did also attempt to develop a measure of orthographic typicality for nouns and verbs. It is unclear why phonological typicality has been used as a proxy for this in studies concerned with the visual sensory processing of written words, rather than this direct measure of orthographic typicality.

¹⁰ Unfortunately, there is no simple way of obtaining estimates from E-Z Reader of how often the saccade will still be in a labile stage by the time all of these other processes complete. Furthermore, the implemented version of E-Z Reader does not allow a user to simply skip the lexical processing of the relative clause noun and immediately proceed to integrating this into

the sentential representation. Due to this, we instead used R to produce random distributions of each relevant process from E-Z Reader, based on the parameter values and standard deviations presented in Reichle, Warren, and McConnell (2009). We then calculated how often the duration of the labile stage of saccadic programming would last longer than the other relevant processes combined. The R Script used for this is provided at the same web address as our data sets and analysis scripts. It should also be noted that we assumed integration of the parafoveal word's syntactic class would take on average 25ms, the same amount of time as integrating a word which has been lexically identified. In reality integration is likely to be faster than this in our study, due to there being no semantic integration necessary at this point. We acknowledge that this is not a proper E-Z Reader simulation.

Table 1

Estimated Fixed-Effects Values from our Linear Mixed Models for Experiment 1. Estimates were obtained in log-transformed values, and subsequently transformed back into fixation times for interpretability.

	Normal Casing		Upper Casing	
	SRC	ORC	SRC	ORC
Total Sentence Reading Time	3124	3294	3368	3498
	Pre-Target Region			
Gaze Duration	192	212	193	192
Go-Past Time	213	247	213	206
Skipping Probability	.59	.58	.55	.55
Last Fixation Duration	185	206	189	190
	Relative Clause Region			
First Pass Time	512	450	540	553
Go-Past Time	584	577	637	675
Total Reading Time	710	719	777	850
Regression Probability	0.07	0.17	0.09	0.14

Means calculated on the basis of raw data can be seen in Table S1 in our supplementary materials.

Table 2

Fixed Effect Estimates, Standard Errors, and t-values from Linear Mixed Models for pre-target region *who* in Experiment 1.

Effect	Gaze Duration			Go-Past Time			Skipping prob.			Last Fixation Duration		
	<i>B</i>	SE	<i>t</i>	<i>b</i>	SE	<i>t</i>	<i>b</i>	SE	<i>z</i>	<i>b</i>	SE	<i>t</i>
Clause Type	-0.05	0.02	-2.69	-0.06	0.03	-2.13	0.03	0.16	0.35	-0.06	0.02	-3.66
Capitalization	-0.05	0.02	-2.36	-0.09	0.03	-3.13	-0.16	0.09	-1.79	-0.03	0.02	-1.93
Interaction	0.09	0.04	2.26	0.19	0.05	3.74	-0.01	0.17	-0.06	0.10	0.03	3.32
Fixation location	-	-	-	-	-	-	-	-	-	-0.03	0.01	-3.91
Contrast 1	-0.10	0.03	-3.16	-0.15	0.04	-4.11	-	-	-	-0.10	0.03	-2.92
Contrast 2	-0.00	0.02	-0.17	0.04	0.03	1.20	-	-	-	-0.03	0.02	-0.26
Fixation Location	-	-	-	-	-	-	-	-	-	-0.03	0.01	-4.17

Contrast 1 refers to a comparison between object and subject relative clause sentences presented in normal casing, while Contrast 2 makes this comparison for sentences written entirely in upper case. Significant terms are presented in bold. A statistical analysis on untransformed data can be viewed in Table S2 of our supplemental material.

Table 3

Fixed Effect Estimates, Standard Errors, and t-values from the Linear Mixed Models for Fixations on the Relative Clause and Across the Whole Sentence for Experiment 1.

Effect	RC-First Pass Time			RC-Go-Past Time			RC-Total Reading Time			RC-Regression Probability			Whole Sentence Reading Time		
	<i>B</i>	SE	t	<i>b</i>	SE	t	<i>b</i>	SE	t	<i>b</i>	SE	z	<i>b</i>	SE	t
Clause Type	-0.05	0.02	-2.69	-0.06	0.03	-2.13	0.03	0.16	0.35	-0.06	0.02	-3.66	-0.05	0.01	-3.67
Capitalization	-0.04	0.02	-2.36	-0.09	0.03	-3.13	-0.16	0.09	-1.79	-0.03	0.02	-1.93	0.06	0.01	5.99
Interaction	0.09	0.04	2.26	0.19	0.05	3.74	-0.01	0.17	-0.06	0.10	0.03	3.32	0.01	0.02	0.46
Contrast 1	-0.10	0.03	-3.16	-0.15	0.04	-4.11	-	-	-	-0.10	0.03	-2.92	-0.06	0.02	-3.18
Contrast 2	-0.00	0.02	-0.17	0.04	0.03	1.20	-	-	-	-0.03	0.02	-0.26	-0.04	0.02	-2.69

Contrast 1 refers to a comparison between object and subject relative clause sentences presented in normal casing, while Contrast 2 makes this comparison for sentences written entirely in upper case. Significant terms are presented in bold. A statistical analysis on untransformed data can be viewed in Table S3 of our supplemental material.

Table 4

Estimated Fixed-Effects Values from our Linear Mixed Models in Experiment 2. Estimates were obtained in log-transformed values, and subsequently transformed back into fixation times for interpretability.

	Valid Preview		Invalid Preview	
	SRC	ORC	SRC	ORC
Total Sentence Reading Time	3023	3124	3035	3204
	Pre-Target Region			
Gaze Duration	188	194	183	191
Go-Past Time	201	203	195	204
Skipping Probability	.64	.62	.70	.63
Last Fixation Duration	186	192	182	192
	Relative Clause Region			
First Pass Time	517	477	511	496
Go-Past Time	567	579	596	610
Total Reading Time	680	693	707	745
Regression Probability	0.05	0.11	0.07	0.13

Means calculated on the basis of raw data can be seen in Table S4 in our supplementary materials.

Table 5

Fixed Effect Estimates, Standard Errors, and t-values from Linear Mixed Models for the Pre-Target Region in Experiment 2.

Effect	Gaze Duration			Go-Past Time			Skipping Probability			LFD		
	<i>B</i>	SE	t	<i>b</i>	SE	t						
Clause Type	-0.04	0.02	-1.87	-0.03	0.03	-1.00	0.18	0.08	2.28	-0.04	0.02	-2.47
Preview	-0.02	0.02	-1.14	-0.01	0.02	-0.63	0.16	0.08	1.99	-0.01	0.02	-0.69
Interaction	-0.01	0.04	-0.40	-0.04	0.05	-0.71	0.27	0.17	1.64	-0.02	0.03	-0.55
Fixation Location	-	-	-	-	-	-	-	-	-	-0.03	0.01	-3.45
Contrast 1	-	-	-	-	-	-	0.05	0.12	0.45	-0.04	0.02	-1.45
Contrast 2	-	-	-	-	-	-	0.32	0.12	2.71	-0.05	0.03	-1.98
Fixation Location	-	-	-	-	-	-	-	-	-	-0.03	0.01	-3.38

Contrast 1 refers to a comparison between object and subject relative clause sentences with a valid preview, while Contrast 2 makes this comparison for sentences including invalid parafoveal previews. Significant terms are presented in bold. A statistical analysis on untransformed data can be viewed in Table S5 of our supplemental material.

Table 6

Fixed Effect Estimates, Standard Errors, and t-values from Linear Mixed Models in Experiment 2 for Relative Clause Reading and Sentence Reading.

Effect	RC-First Pass Time			RC-Go-Past Time			RC-Total Reading Time			RC-Regression Probability			Whole Sentence Reading Time		
	<i>B</i>	SE	<i>T</i>	<i>b</i>	SE	<i>t</i>	<i>b</i>	SE	<i>t</i>	<i>b</i>	SE	<i>z</i>	<i>B</i>	SE	<i>t</i>
Clause Type	0.06	0.02	2.86	-0.02	0.02	-1.43	-0.04	0.01	-2.49	-0.82	0.16	-5.24	-0.04	0.01	-3.95
Preview	0.01	0.02	0.73	0.05	0.01	3.91	0.06	0.01	3.94	0.27	0.13	2.15	0.01	0.01	1.56
Interaction	-0.05	0.03	-1.47	-0.00	0.03	-0.07	-0.03	0.03	-1.07	0.24	0.25	0.96	-0.02	0.02	-1.13
Contrast 1	0.08	0.03	2.90	-	-	-	-0.02	0.02	-0.80	-0.77	0.17	-4.43	-0.03	0.01	-2.82
Contrast 2	0.03	0.03	1.13	-	-	-	-0.05	0.02	-2.25	-0.65	0.17	-3.75	-0.05	0.01	-4.63

Contrast 1 refers to a comparison between object and subject relative clause sentences with a valid preview, while Contrast 2 makes this comparison for sentences including invalid parafoveal previews. Significant terms are presented in bold. A statistical analysis on untransformed data can be viewed in Table S6 of our supplemental material.

Table 7

Estimated Fixed-Effects Values from our Linear Mixed Models for Experiment 3. Estimates were obtained in log-transformed values, and subsequently transformed back into fixation times for interpretability.

	SRC	ORC
Total Sentence Reading Time	3477	3644
Pre-Target Region		
Gaze Duration	203	217
Go-Past Time	214	240
Skipping Probability	.61	.55
Last Fixation Duration	200	213
Relative Clause Region		
First Pass Time	531	465
Go-Past Time	606	585
Total Reading Time	760	771
Regression Probability	0.07	0.14

Means calculated on the basis of raw data can be seen in Table S7 in our supplementary materials.

Table 8

Effects Estimates, Standard Errors, and t-values from Linear Mixed Models in Experiment 3 for the Pre-Target Region.

Effect	Gaze Duration			Go-Past Time			Skipping			Last Fixation Duration		
	<i>B</i>	SE	<i>t</i>	<i>B</i>	SE	<i>t</i>	<i>b</i>	SE	<i>Z</i>	<i>b</i>	SE	<i>T</i>
Clause Type	0.07	0.02	4.14	0.11	0.02	5.68	-0.23	0.08	-2.81	0.06	0.01	4.75
Fixation Location										0.00	0.02	0.13
Fixation Location ²										-0.01	0.01	-2.25

Significant effects are presented in bold. A statistical analysis on untransformed data can be viewed in Table S8 of our supplemental material.

Table 9.

Fixed Effect Estimates, Standard Errors, and t-values from Linear Mixed Models in Experiment 3 for Relative Clause and Sentence Reading.

Effect	RC-First Pass Time			RC-Go-Past Time			RC-Total Reading Time			RC-Regression Probability			Whole Sentence Reading Time		
	<i>B</i>	SE	T	<i>b</i>	SE	t	<i>b</i>	SE	t	<i>b</i>	SE	z	<i>B</i>	SE	t
Clause Type	-0.14	0.02	-6.65	-0.04	0.02	-2.20	0.01	0.02	0.82	0.73	0.13	5.56	0.05	0.01	5.47

Significant terms are presented in bold. A statistical analysis on untransformed data can be viewed in Table S9 of our supplemental material.

Table 10

Output from our Bayesian LMMs for our data and the data of Rayner & Schotter. Log-transformed values from the model are presented, with these values being transformed back into a millisecond scale in the brackets for the sake of interpretability. For the two boundaries of the credible interval we present the boundary with the smaller magnitude as the lower end and the larger magnitude as the upper end.

	Intercept	RC-CrI-L95	RC-Median	RC-CrI-U95
Pre-target Region				
Gaze Duration	5.28 (196)	0.04 (8)	0.07 (15)	0.09 (19)
Go-Past Time	5.34 (209)	0.06 (12)	0.09 (19)	0.12 (26)
Last Fixation Duration	5.25 (191)	0.04 (7)	0.06 (11)	0.09 (18)
Skipping Probability	0.51 (0.64)	-0.03 (-0.01)	-0.15 (-0.03)	-0.27 (-0.06)
Relative Clause Region				
First Pass Time	6.38 (590)	-0.09 (-51)	-0.12 (-67)	-0.15 (-82)
Go-Past Time	6.40 (602)	0.01 (6)	-0.02 (-12)	-0.05 (-20)
Total Reading Time	6.57 (713)	-0.02 (-34)	0.01 (8)	0.05 (37)
Regression Probability	0.03	0.03	0.04	0.06
Total Sentence Time	8.03 (3072)	0.03 (93)	0.05 (157)	0.06 (190)
Rayner & Schotter pre-target				
Gaze duration	5.42 (226)	-0.01 (-2)	0.02 (4)	0.05 (11)
Go-Past Time	5.53 (252)	-0.03 (-7)	0.00 (2)	0.04 (10)
Last Fixation Duration	5.31 (202)	-0.02 (-4)	0.01 (2)	0.03 (7)